Utilizing Four Dimensional Lightning and Dual-Polarization Radar to Develop Lightning Initiation Forecast Guidance

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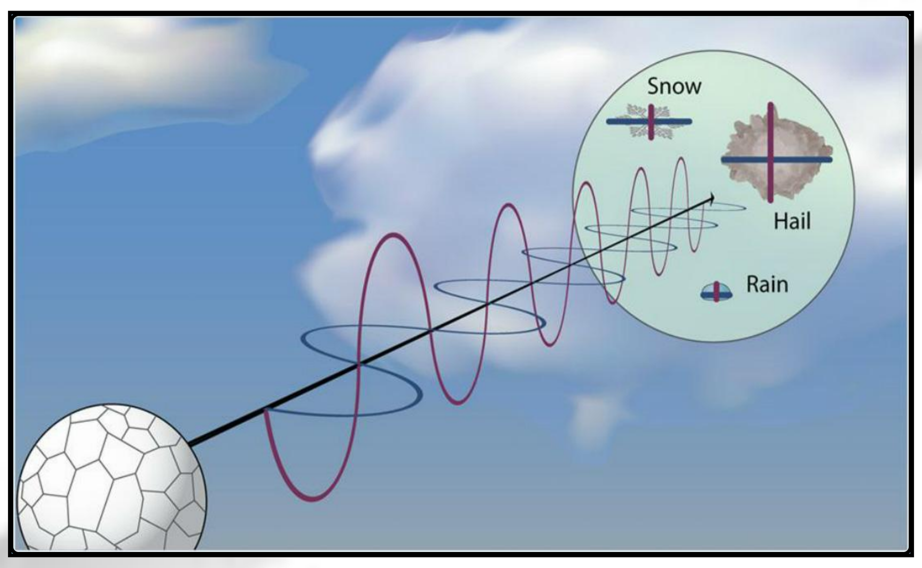
Abstract:

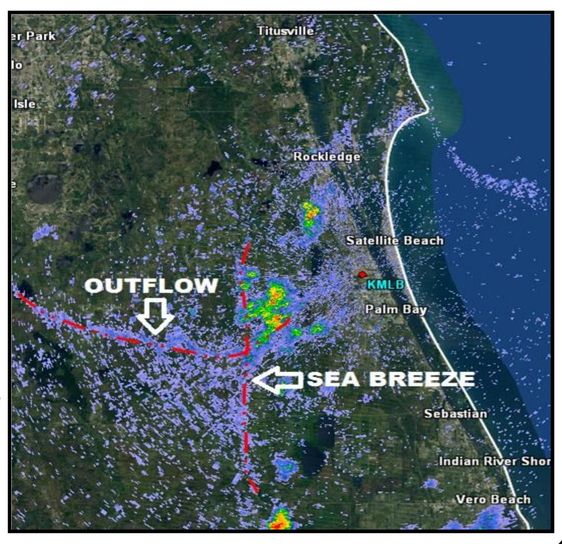
Lightning initiation from airmass thunderstorms is a major forecast challenge faced by Air Force's 45th Weather Squadron (45 WS), which provides weather support to Cape Canaveral Air Force Station and Kennedy Space Center (KSC). Prior studies by Thurmond (2014) and Woodard (2011) have shown that dual-polarization (DP) radar can be used to identify the presence of hydrometeors indicative of cloud charging, leading to improved lightning initiation forecasts. This 45 WS currently uses empirical lightning initiation forecast rules which state that in-cloud lightning is likely within 10 to 20 minutes after radar reflectivity exceeds 37 dBZ above the -10°C level. Rules also exist for cloud-to-ground, anvil, and debris cloud lightning. This study examined 200+ lightning-producing and non-lightning convective cells from March 2012 to March 2014 in order to expand the existing empirical forecast principles to incorporate DP parameters. In-cloud and cloud-to-ground lightning flash data were obtained from the KSC Four Dimensional Lightning Surveillance System (4DLSS), and DP radar data were obtained from the Melbourne, Florida WSR-88D. Lightning initiation forecast lead times, probability of detection, and false alarm rates were compared between a number of candidate DP-based forecast techniques and the current techniques employed by 45 WS.

Background:

- *45 WS forecasters issue 2,500+ lightning advisories per year*
- *Lightning is a leading cause of launch scrubs/delays*
- *Impact 5,000+ ground ops per year and 25,000+ personnel*
- *Lightning forecasts are difficult in FL due to numerous weak boundary interactions*
- *Current lightning forecast techniques employed by 45 WS do not utilize DP radar*
- *DP shown to improve lightning onset forecasts (Thurmond, 2014 and Woodard, 2011)*



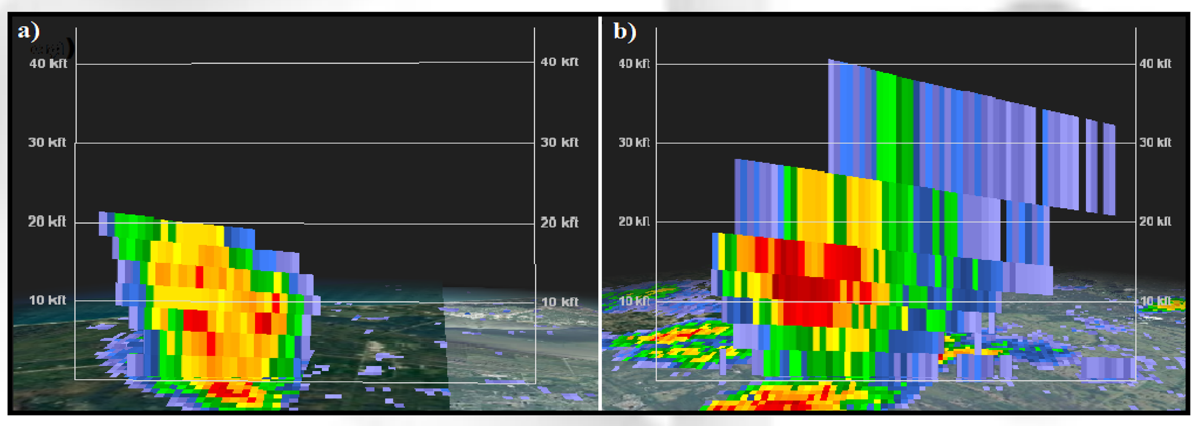
Left: WSR-88Ds across the US upgraded to DP capability in 2012. EM pulses now have both a horizontal and vertical polarization. This provides more information on the size and shape of hydrometeors within a volume scan. DP can identify mixed phase hydrometeors that indicate charging regions within developing storms.



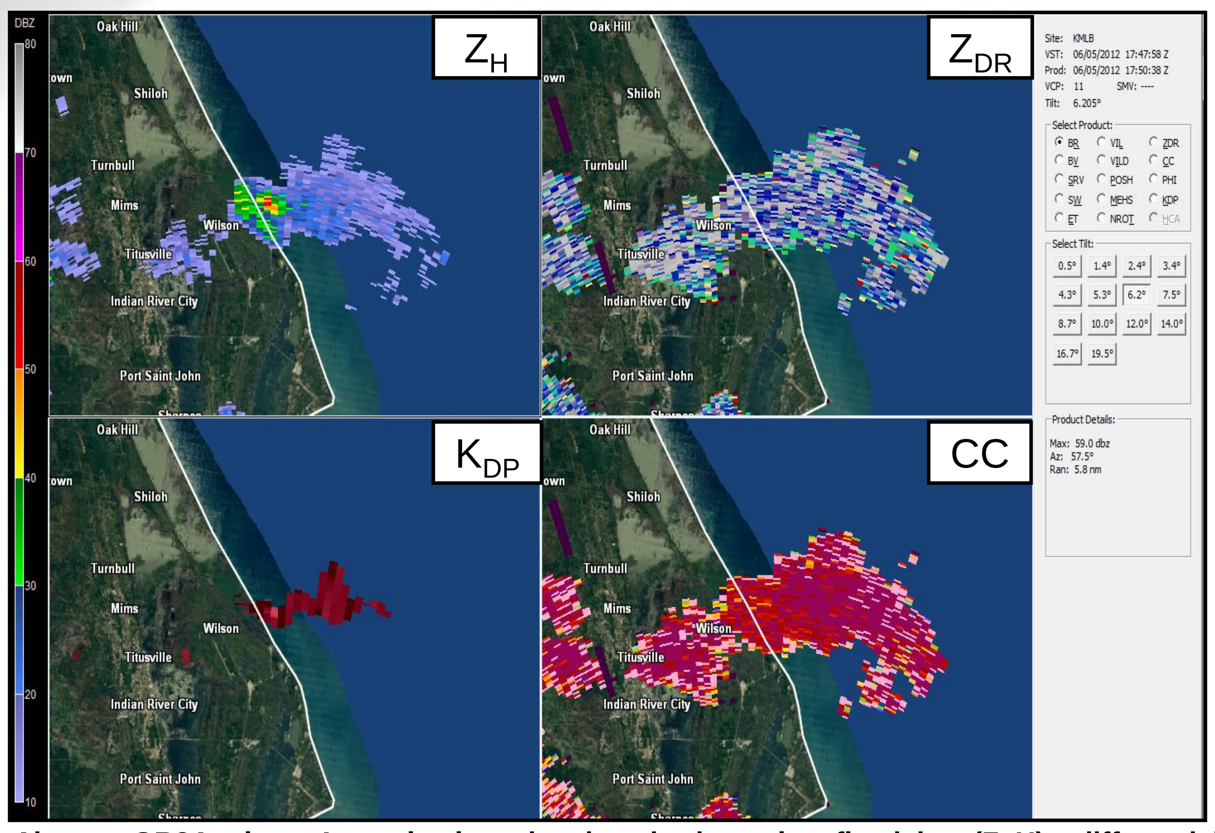
Right: Radar image showing thunderstorms forming along the intersection of a sea breeze and remnant outflow boundary. Weak boundary interactions like this one are the forcing mechanisms for airmass thunderstorms in Florida.

Methodology:

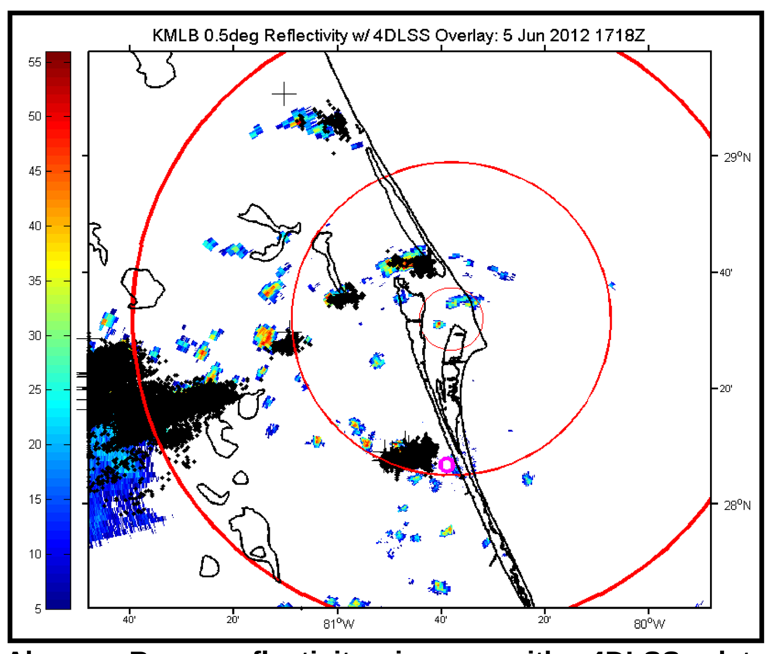
- *Collected database of 284 days with discrete convective cells*
- *Cells from a two-year period between Mar 2012 to Mar 2014*
- *Lightning data obtained from 4DLSS archive at KSC*
- *4DLSS contains aloft (LDAR) and cloud-to-ground (CGLSS) data*
- *Used MATLAB to sort through 4DLSS data (45,000+ text files)*
- *Radar archive obtained for KMLB WSR-88D from NCDC*
- *Created training dataset to determine thresholds to test*
- *Training set contained 74 lightning & 51 non-lightning cells*
- *Examined Z, ZDR, KDP at -5°C, -10°C, -15°C, -20°C heights*
- *KXMR soundings used to establish height of thermal levels*
- *Tested training dataset thresholds on validation dataset*
- *Validation set contained 73 lightning & 51 non-lightning cells*
- *Used MATLAB and GR2Analyst to interrogate radar data*
- *All cells analyzed were within 100km of KSC*



Left: GR2Analyst cross-sections examining two separate cells. Cross-sections provided valuable information about the structure of the updraft core. However, these two cells were removed from the database due to the volume coverage pattern not seeing the top of the storm (a), or due to the scan elevation angle passing through multiple thermal levels of interest (b).



Above: GR2Analyst 4-panel plot showing horizontal reflectivity (Z_H), differential reflectivity (ZDR), specific differential phase (KDP), and correlation coefficient (CC or ρHV). Each DP parameter was examined with the exception of CC, which was found to be too noisy of an indicator.



Above: Base reflectivity image with 4DLSS data overlaid. A black dot indicates an LDAR detection while a black plus sign indicates a CGLSS detection. The three closest cells with lightning to the north and west of KSC/CCAFS are ideal lightning producing cells for this study while the two cells directly over KSC/CCAFS are ideal non-lightning producers.

Radar Equations:

Power Equation:

$$P_r = \frac{\pi^3 P_t g^2 \theta \phi c t |K|^2 l z}{1024 \ln(2) \lambda^2 r^2}$$

Radar Reflectivity Value:

$$Z = 10 \log_{10} \frac{z}{1mm^6/m^3}$$

Differential Reflectivity:

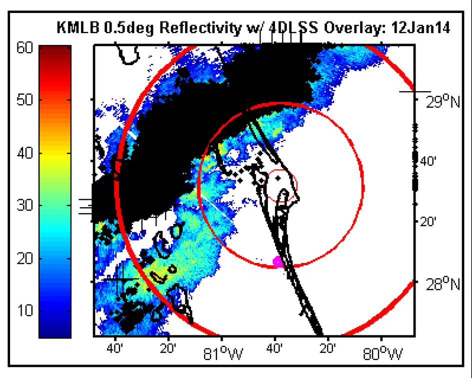
$$Z_{DR} = Z_H - Z_V$$

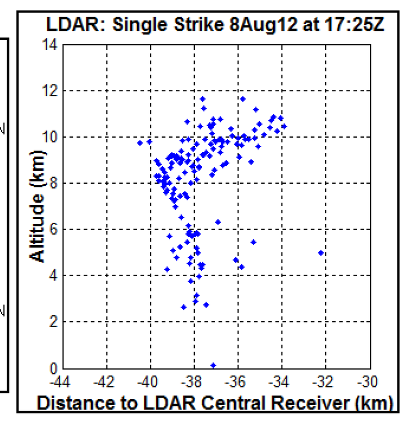
Differential Phase:

$$\phi_{DP} = \phi_{HH} - \phi_{VV}$$

Specific Differential Phase:

$$K_{DP} = \frac{\phi_{DP}(r_2) - \phi_{DP}(r_1)}{2(r_2 - r_1)}$$





Above Left: Base reflectivity image with 4DLSS data overlaid. Days with organized lines of thunderstorms were not analyzed in this study.

Above Right: A sample (X, Z) LDAR plot showing the height of the stepped leaders detected by the system.

Results:

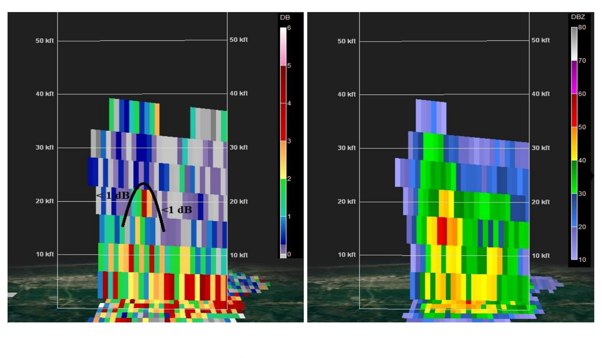
- *Training dataset cells analyzed starting 50 mins before lightning initiation*
- *Non-lightning cells analyzed 50 mins before maximum height achieved*
- *Training results separated by thermal level and time bin, then analyzed*
- *Performed t-tests, analyzed scatter plots, ran signal detection techniques*
- *Established 18 forecast algorithms to test against 2 baseline algorithms*
- *Algorithms designed for max detection & lead times with low false alarms*

-10°C Thermal Level Thresholds	POD	FAR	CSI	Average Lead Time	Median Lead Time	OUI
37dBZ/1nm Width	***0.740***	***0.053***	***0.711***	***07:53***	***05:18***	***0.631***
37dBZ	***0.849***	***0.101***	***0.775***	***11:42***	***06:28***	***0.702***
35dBZ	0.918	0.163	0.779	12:09	07:29	0.704
36.5dBZ	0.918	0.118	0.817	11:39	06:19	0.730
35dBZ/.31Z_{DR}	0.904	0.143	0.786	12:09	07:34	0.710
36.5dBZ/.31Z_{DR}	**0.890**	**0.058**	**0.844**	**11:45**	**06:36**	**0.750**
35dBZ/.31Z_{DR} or 41dBZ	0.890	0.122	0.793	12:16	07:38	0.718
35dBZ/AnyK_{DP}	0.795	0.065	0.753	09:53	05:28	0.675
36.5dBZ/AnyK_{DP}	0.775	0.083	0.724	09:56	05:18	0.657
35dBZ/.31Z_{DR}/AnyK_{DP}	0.795	0.049	0.763	09:53	05:28	0.682

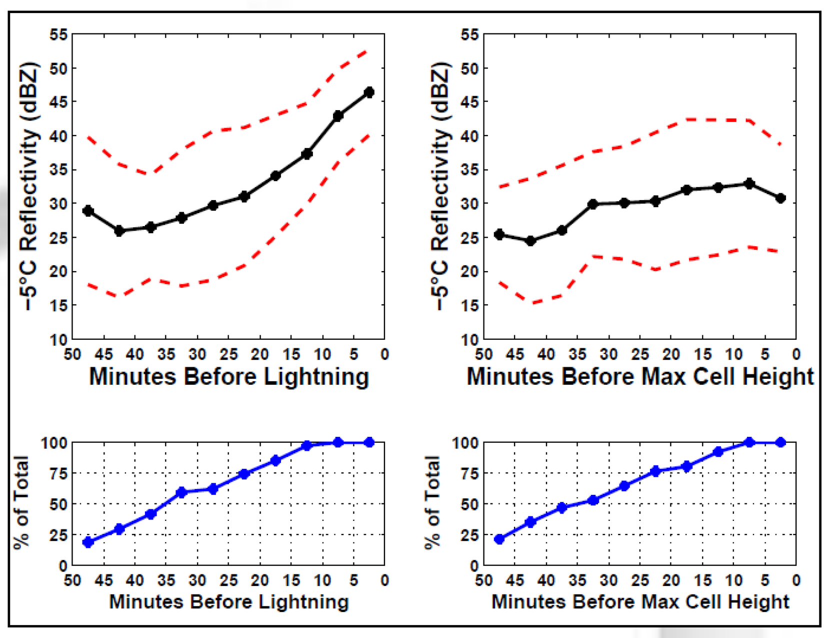
-5°C Height Thresholds	POD	FAR	CSI	Average Lead Time	Median Lead Time	OUI
40.5dBZ/1nm Width	0.822	0.143	0.723	10:49	07:23	0.655
40.5dBZ	0.918	0.212	0.736	13:27	10:38	0.678
40.5dBZ/.81Z_{DR}	0.890	0.177	0.747	12:43	10:27	0.685
40.5dBZ/.81Z_{DR} or 46.5dBZ	0.890	0.177	0.747	12:46	10:27	0.685
42dBZ/.81Z_{DR}	0.849	0.151	0.738	12:30	09:59	0.679
40.5dBZ/AnyK_{DP}	0.918	0.202	0.744	13:11	10:28	0.683
42dBZ/AnyK_{DP}	0.890	0.188	0.739	12:28	08:41	0.675
40.5dBZ/.81Z_{DR}/AnyK_{DP}	**0.890**	**0.167**	**0.756**	**12:29**	**09:31**	**0.690**

Upper Left Table: Thresholds tested at -10°C using the validation dataset. Forecast metrics were calculated for each threshold (not all tested are shown). OUI is the Operational Utility Index, developed by 45 WS. The baseline thresholds are in bold and italics. The best method is bolded.

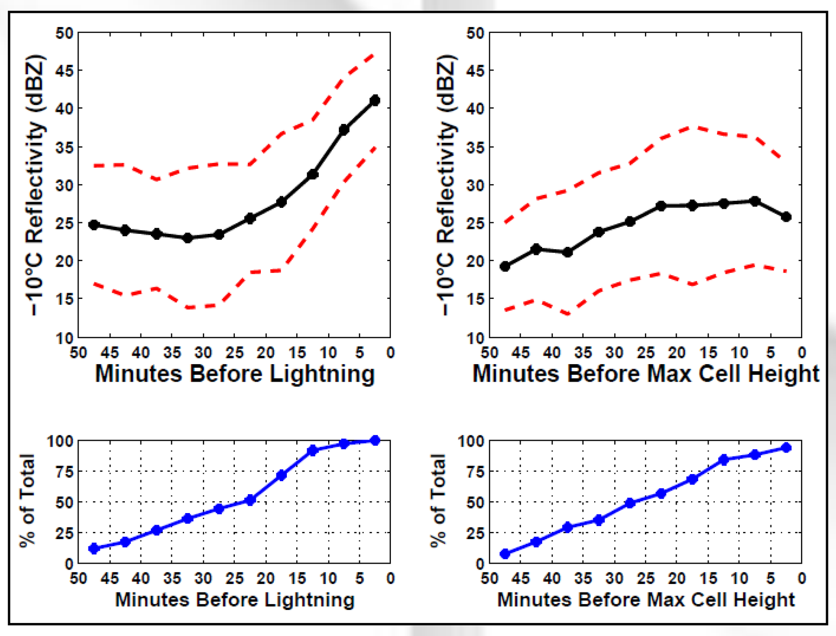
Lower Left Table: Thresholds tested at -5°C using the validation dataset. The best method is bolded.



Above: GR2Analyst cross-section showing a ZDR column within the updraft. These columns can charging regions allowing ZDR to be a valuable threshold.



Above: -5°C mean reflectivity for lightning and non-lightning cells. Red dashed lines are +/-1 standard deviation from the mean. Means 15 mins and earlier were statistically significant at this level based on a paired t-test.



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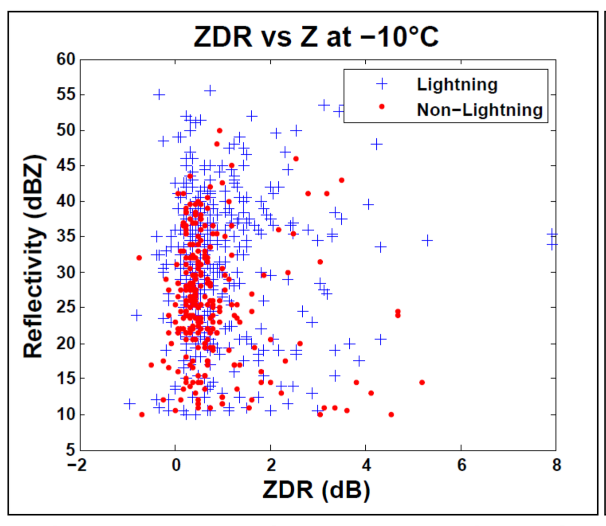

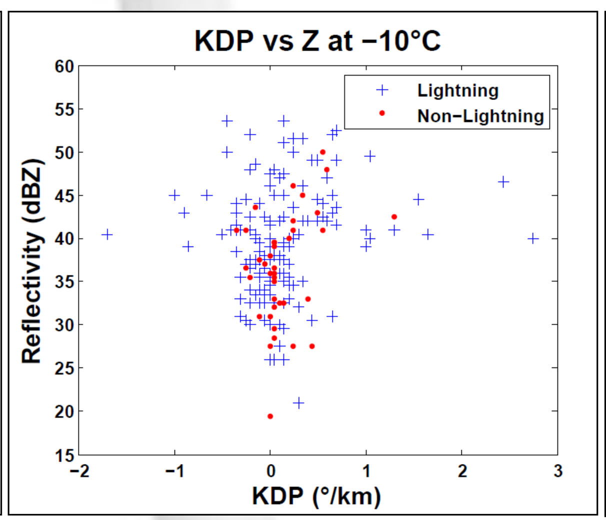

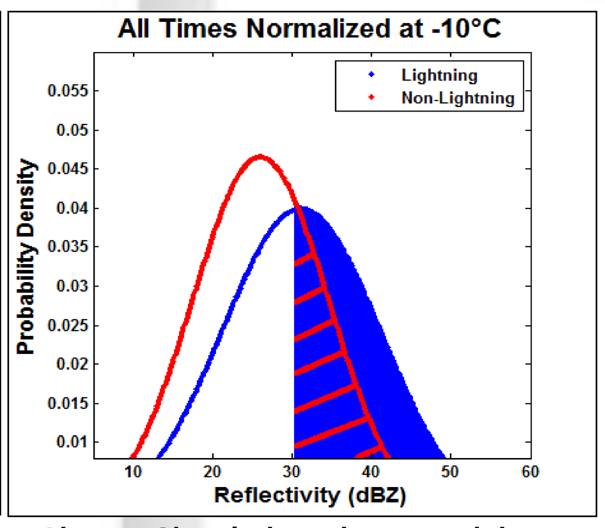

Above: Scatterplots at every thermal level were used to identify DP and reflectivity combination thresholds.

Above: Unlike ZDR, KDP values are unavailable for many cells unless reflectivity is above 30 dBZ.

Above: Signal detection examining a reflectivity threshold set at 30.5 dBZ. Hashed red area identifies false alarms.

Conclusions:

- *Algorithms using DP outperformed the existing methods*
- *Best results from 36.5 dBZ and .31 ZDR at -10°C*
- *Adding ZDR enables lower reflectivity thresholds*
- *KDP showed some promise, but ZDR methods are better*
- *Thresholds at -5°C provide best lead times, but higher FAR*

Future Work:

- *300+ additional cells needed to confirm results w/ 95% confidence*
- *Investigate setting thresholds for consecutive volume scans*

Acknowledgment:

Mr. William Roeder, of 45 WS, provided great knowledge and passion to this project, and a very insightful tour of 45 WS facilities.